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Research on Energy Utilization in Recovery of CO_2 from Boiler Flue Gas

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Abstract

To the 2×40 t/h heating boiler flue gas, ethanolamine was used for absorption, carbamate – for desorption. The waste heated boiler flue gas was used to heat the absorption and the desorption; the pump was driven by the solar energy. The results showed that the best absorption rate was 82.28%, when the ethanolamine concentration was 40% and the temperature was 40°C; the energy consumption was 59.82 KJ/mol. The best desorption temperature was 115°C, the desorption rate was 55%, and its energy consumption was 694.30 KJ/mol. The pump needed 1.49 KJ/h, reduced 42.8 t/year of CO_2 and regenerated 23.54 t/year of CO_2.

Keywords: CO_2 absorption rate, CO_2 desorption rate, CO_2 regeneration rate, energy conservation, emission reduction

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1. Introduction

In recent years, the concentration of CO_2 in the atmosphere has increased yearly. Before the Industrial Revolution, the concentration of CO_2 in the atmosphere was 280 ppm. In 2016, the World Meteorological Organization (WMO) announced that the concentration of CO_2 in the global atmosphere exceeded 400 ppm for the first time. The total CO_2 emission in 2016 of China is about 8 billion tons, provided that about more than 60% of CO_2 comes from the power and heat industries [1]. CO_2 in the atmosphere is one of the main culprits of global warming. If industrial CO_2 is collected, it can be used to make industrial products such as dry ice, soda ash, and urea. Therefore, research on CO_2 recovery and utilization in boiler flue gas has become an important topic for Chinese researchers.

At present, the CO_2 capture of boilers mainly utilizes the chemical absorption method, because this method has high decarburization rate, low decarburization cost, and remarkable effect. In this article, for the flue gas of 2×40 t/h coal-fired boiler, CO_2 is captured by ethanolamine and sodium hydroxide under experimental conditions.

The parameters of the flue gas of 2×40 t/h coal-fired boiler are shown in Table 1. The volume concentration of CO_2 gas is about 13%. In order to facilitate the reading of the rotameter, the volume concentration of simulated CO_2 gas is 14%.

Table 1: Flue gas parameters of 40 t/h coal fired boiler.

Heading	Flue Gas Temperature (°C)	Pressure (MPa)	Exhaust Flow Rate (m/s)	Exhaust Flow (m^3/h)	Standard Dry Exhaust Flow (m^3/h)
Average value	135	0.098066	3.99	129361.40	92070.46
Maximum	168	0.098120	4.05	131283.70	96577.34
Minimum	95	0.097983	3.74	121168.00	56276.74
Number of samples	30	30	30	30	30

2. Experiment

The CO_2 trap consists of a gas cylinder, a rotameter, a pressure reducing valve, a mixing buffer, an electrothermal thermostatic water bath, a thermometer, and a three-necked flask (Figure 1). First, the absorbent is heated in the constant temperature water bath to the experimental temperature. Then, using the CO_2 cylinder and the N_2 cylinder, the pressure is adjusted by reducing valve to obtain the experimental condition flow. Finally, the gas is mixed by the mixing buffer and flows to the absorbent.

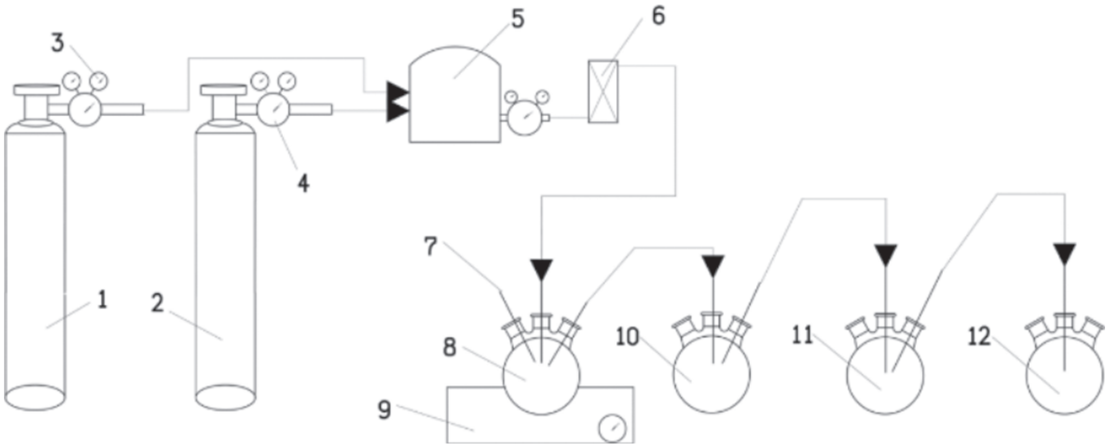

Figure 1: Schematic diagram of absorption experiment: 1 – CO_2 cylinder; 2 – N_2 cylinder; 3, 4 – pressure-reducing valves; 5 – mixing buffer device; 6 – rotameter; 7 – thermometer; 8 – absorbent; 9 – constant temperature water bath; 10 – first-level NaOH solution; 11 – second-level NaOH solution; 12 – third-level NaOH solution.

The pressure reducing valves of the CO_2 and N_2 cylinders can be adjusted to obtain flow rates of 0.8 and 4.8 L/min. The volume concentration of CO_2 gas in the mixed gas was 14.28%, which was very close to the volume concentration of CO_2 gas in the coal-fired boiler. The flow was maintained for 5 minutes, the total mass of CO_2 during the time was M. In this experiment, to obtain an optimal absorption coefficient, we used different concentrations of ethanolamine solution to absorb CO_2 under different temperature conditions. Given the rate of absorption of ethanolamine could not be directly measured, so the three-necked flask in Figure 1 was used to capture CO_2 that was not absorbed by ethanolamine. By the use of a three-stage absorption device, we could absorb more than 97% of CO_2, and the experimental error has greatly reduced [2]. The absorbent was sodium hydroxide solution, and the product was Na_2CO_3, which continuously reacted with $BaCl_2$ to form $BaCO_3$ precipitate:

$$BaCl_2 + Na_2CO_3 = BaCO_3 \downarrow + 2NaCl \tag{1}$$

We filtered, dried, and weighed the $BaCO_3$ precipitate to obtain its mass. By the way, the Na_2CO_3 mass was also calculated.

Experimental instruments and reagents used are presented in Table 2.

Table 2: Experimental instruments and reagents.

Instrument/Reagents	**Model/Manufacturer**
Electric thermostatic water bath	Model 8002, Beijing Huabolian Medical Equipment Co., Ltd.
Magnetic stirrer	EMS-4A type, Shanghai Yingdi Instrument Equipment Co., Ltd.
Heating CO_2 decompression flow vessel	YQT-341,Qingdao Yulongyuan Welding & Cutting Equipment Co., Ltd.
Nitrogen pressure reducing flow device	YQAr-731L, Qingdao Yulongyuan Welding & Cutting Equipment Co., Ltd.
Electronic balance	JA1003, Shanghai Shunyuhengping Scientific Instrument Co., Ltd.
Electric blast drying oven	CS101-2A, China Chongqingyinhe Test Instrument Co., Ltd.
Ethanolamine	Tianjin Kemiou Chemical Reagent Co., Ltd.
Sodium hydroxide	Tianjin Hedong District Hongyan Reagent Factory
Ammonia with a mass fraction of 25% to 27%	Xi'an Jianxiang Chemical Co., Ltd.
Barium chloride	Zhengzhou Zhiyuan Chemical Products Co., Ltd.

The sodium hydroxide solution was used as an absorbent, which absorbed CO_2 to form Na_2CO_3.

$$2NaOH + CO_2 = Na_2CO_3 + H_2O,\ \Delta H = -171.8 KJ/mol. \tag{2}$$

The ethanolamine reacted with CO_2 to form a carbamate, and the carbamate was pyrolyzed to ethanolamine and CO_2 by the following reaction:

$$CO_2 + 2HOC_2H_4NH_2 \Leftrightarrow HOC_2H_4NH_3COONHC_2H_4OH, \Delta \mathrm{H} = \mp 72.7\ \mathrm{KJ/mol}. \tag{3}$$

Carbamate desorption device diagram is presented in Figure 2. Thermal analysis of the absorption reactions is presented in Table 3.

TABLE 3: Thermal analysis of the absorption reactions.

Physical Properties	Ethanolamine
Reaction heat (KJ/mol)	−36.35
Dissolve heat (KJ/mol)	0
Specific heat capacity (kJ/(kg·°C))	3.4
Energy consumption (KJ/mol)	191.44

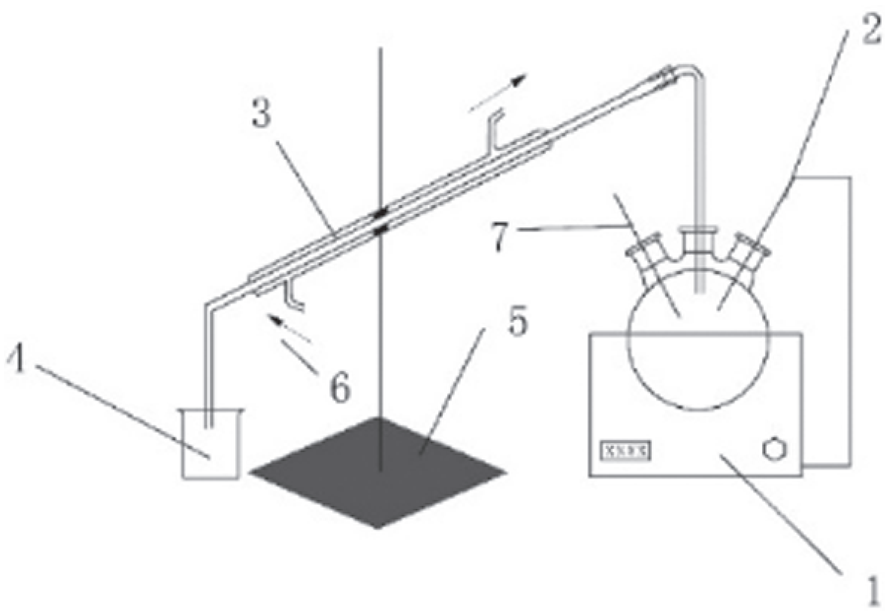

Figure 2: Carbamate desorption device diagram: 1 – intelligent thermostat heating sleeve; 2 – sensor; 3 – condenser; 4 – sodium hydroxide solution; 5 – iron stand; 6 – cooling water; 7 – thermometer.

The absorption rate of the ethanolamine absorbent is calculated as follows:

$$\eta = \frac{M - M_1}{M} \times 100\%. \tag{4}$$

In the formula, M_1 is the mass of CO_2 absorbed by the tertiary absorption device, M is the total mass of CO_2 after 5 minutes of cylinder aeration.

3. Results and Discussion

As shown in Figure 3, the highest absorption rate is at 40°C, and the temperature in the absorption tower of industrial decarbonization system is 30~60°C [3]. The optimum temperature for absorption of CO_2 by ethanolamine is 40°C, the concentration is 40%, and the absorption rate is 82.28%.

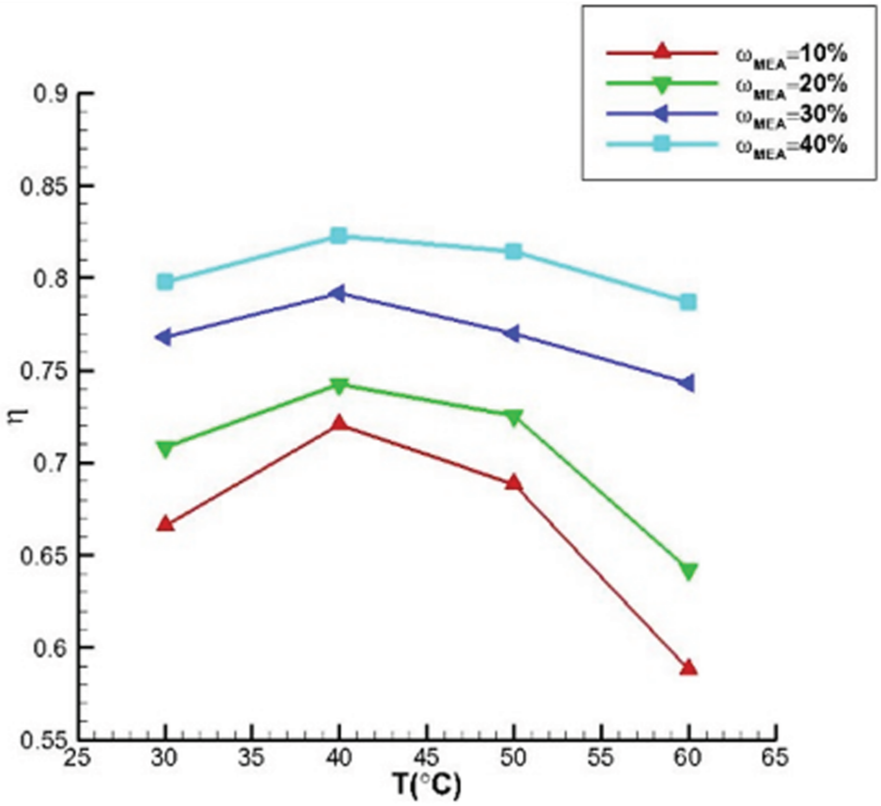

Figure 3: Effect of temperature on ethanol amine absorption.

It can be seen from Figure 4 that as the temperature increases, the desorption rate of the carbamate solution also becomes larger, and the desorption rate is the lowest at 100°C. From 110 to 115°C, the fold line is the steepest and the desorption rate is the highest, indicating that desorption is the best in this temperature range. The carbamate has the highest desorption rate at around 115°C, with a value of 55%, and then tends to be gentle with increasing temperature.

4. Energy Source of Boiler Flue Gas CO_2 Capture System

According to the experimental results, the CO_2 absorption-desorption device is applied to a 2×40 t/h coal-fired boiler. The waste heat of flue gas is used to heat the system. The design calculation and schematic of the device are as follows.

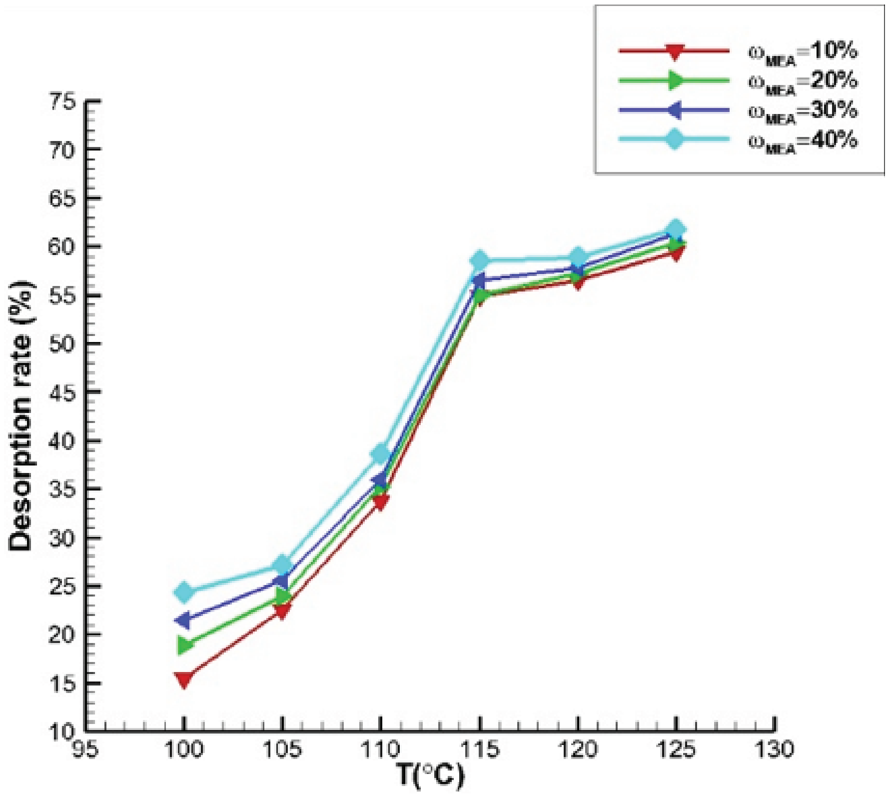

Figure 4: Effect of temperature on carbamate desorption rate.

4.1. Energy balance

The ethanolamine absorbent absorbs CO_2 under heating conditions, and the different components result in different specific heat capacities, so the absorbed heat is different.

$$Q_{solution} = (W_1 C_{P1} + W_2 C_{P_2})(t_b - t_a) - (\Delta H_S)_{t_a} + (\Delta H_S)_{t_b} \quad (5)$$

The general equation is:

$$Q_{In} = Q_{solution} + \Delta \mathrm{H} \quad (6)$$

The energy flow diagram of the CO_2 capture system is shown in Figure 5.

4.2. Calculation of flue gas waste heat utilization system

The nominal dry exhaust flow rate is 9.20×10^4 m^3/h as shown in Table 1, and the average temperature is 135°C. CO_2 flow: q_2 is 6.75×10^3 mol/min. The amount of CO_2 that can be absorbed q_{2a} = 5.55×10^3 mol/min; the amount of ethanolamine Q_3 = 1.11×10^4 mol; the quality of the solution is 1.69×10^3 kg. According to the relevant literature [4], the solubility of CO_2 in 40% ethanolamine solution is 2.94 mol/L at 40°C under

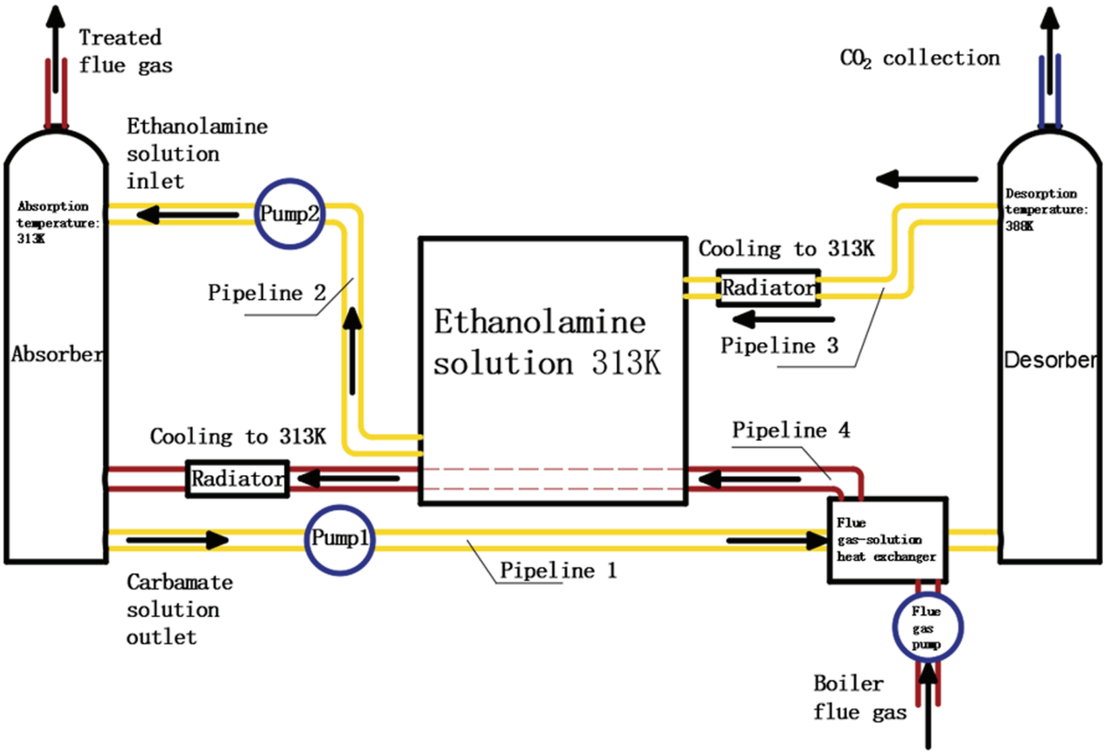

Figure 5: Energy flows in the CO_2 capture system.

atmospheric pressure. The volumetric flow rate of ethanolamine is required every minute: Q_3 = 1.89×10^3 L/min. The transfer rate of carbamate between the absorption–desorption devices q_4 = 92.52 mol/s. According to the concentration of ethanolamine, the concentration of the carbamate solution is 54.40%, the flow rate of the carbamate solution $q_{m4solution}$ = 28.24 kg/s. According to the literature [5], the carbamate density is 7.46×10^2 kg/m^3, which is obtained from the binary organic solution density formula: $\rho_{solution} = 0.86{\times}10^3\ kg/m^3$. Therefore, the volumetric flow rate of the solution in pipeline 1 $q_{v4solution}$ = 2.43×10^4 cm^3/s.

4.3. Energy calculation of the heat exchange system

As can be seen from Table 1, the average temperature of the boiler flue gas outlet is 135°C, and it can be seen from Figure 4 that the optimum temperature of the carbamate desorption process is 115°C. The waste heat of the flue gas is used to heat the carbamate solution to achieve the energy saving effect of the desorption device.

The temperature change of flue gas is Δt_{fg}, the physical property of the flue gas at 135°C are found in the *Industrial Furnace Design Manual*: the density of the flow gas $\rho_{fg} = 88kg/m^3$, the specific heat capacity of the flow gas $c_{fg} = 1.08kJ/kg{\cdot}K$, the density of the solution is $0.86{\times}10^3 kg/m^3$, the flow rate of the solution is 2.43×10^{-2}

m^3/s. According to the literature [5], the specific heat capacity of carbamate c_a = $2.00\times10^2 J/(kg\cdot K)$. Calculated according to the specific heat capacity definition, $c_{solution}$ = $2.31\times10^3 J/(kg\cdot K)$. Heat exchange rate:

$$Q = c_{fg}\times L\times\rho_{fg}\times\Delta_{tfg}= c_{solution}\times q_{v4solution}\times\rho_{solution}\times\Delta_{tsolution} \quad (7)$$

Substituting data, we get the temperature change of the flue gas 63.2°C and the temperature change of the solution 31.8°C. The solution can be heated to 71.8°C by flue gas waste heat. In order to achieve the optimum desorption temperature, steam can be used in the desorption column, $\Delta_{tsteam} = 43.2$℃.

4.4. Packing tower design calculation

The schematic diagram of CO_2 absorption–desorption device design is presented in Figure 6. The ethanolamine solution storage tank volume is designed to be 2.5 m^3, which is used to store the ethanolamine solution required for the reaction. The absorption–desorption device is designed as a packed tower. The tower diameter is set to 2.0 m, and the tower height Z is calculated as follows.

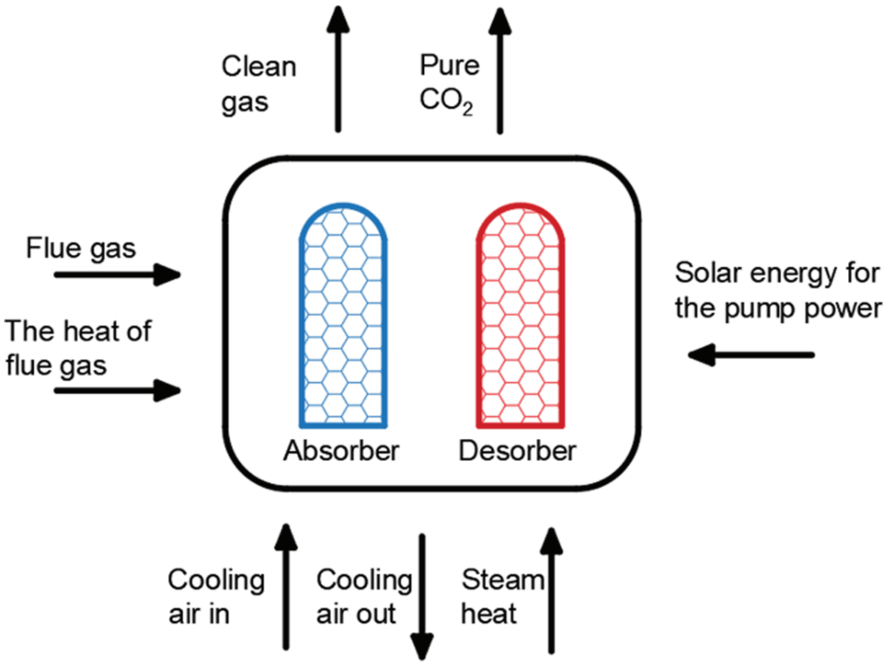

Figure 6: Schematic diagram of CO_2 absorption–desorption device design.

According to mass transfer theory, we can get:

$$Z = H_{OV}N_{OV} = H_{OL}N_{OL}, \quad (8)$$

where H_{OV}, H_{OL} – height of the total mass transfer unit of gas and liquid phase; N_{OV}, N_{OL} – the total mass transfer unit of gas and liquid phase.

We use Dg38 metal Pall ring for packing and after calculation we get Z = 12.44 m.

4.5. Pipeline design calculation

Pipeline 1 represents a stainless steel pipe transfer solution of model DN80 and length 5 m: the diameter d_1 of the pipeline 1 is 80 mm. The flow rate v_1 inside the tube is 4.83 m/s. The volume flow of ethanolamine $q_{v3solution}$ from the desorption unit to the ethanolamine storage tank and the absorption unit is 2.43×10^4 cm^3/s. The diameter of the line 2 is the same as that of the line 1, and the length is 2 m. The pipeline 3 uses 30 stainless steel tubes covered by fins and the model number is DN30 and the length is 5 m. The flow rate v_2 inside the tube is 1.15 m/s.

4.6. Calculation of resistance loss

Since the solution component is mostly water, the physical properties of solution can be approximately calculated as those the water. At 40°C, the density of the water is $9.92\times10^2 kg/m^3$, and the viscosity $\mu\ is\ 0.656\times10^{-3} N.s.m^{-2}$, Re is 6.8×10^5. Therefore, the flow state in the pipes 1 and 2 is turbulent. For line 3, Re is 5.22×10^4. Therefore, the flow state in the pipeline 3 is turbulent. The resistance loss along the path is 8.44 m, the local resistance loss is 0.998 m, the pressure drop is 9.25×10^4 Pa, and the pump work is 2.85×10^3 at the effectiveness of 0.78. According to the existing motor selection, two pump motors with a power of 1.5 kW were selected.

4.7. Calculation of the solar energy systems

The design power of the solar system should satisfy the total power of the motor 3 kW.

12 Yingli YL270P-29b photovoltaic panels were used to construct the photovoltaic array. The maximum output power was 270 W, the open circuit voltage was 37.9 V, the short circuit current was 9.35 A, the maximum working voltage was 31 V, the maximum working current was 8.9 A, and the size was 1650 × 992 × 35 mm^3. We chose 16 HGY6037 batteries to store the excess energy.

Taking Xi'an as an example, the installation inclination of the photovoltaic (PV) model is designed to be 45°, and priority should be given to guarantee the use of electricity in winter. The PV model's wiring design uses a series of 2-way parallel connections. Through simulation, the expected power generation of the system is as follows.

As can be seen, the PV system's annual power generation is 1.20×10^3 kWh. The generating capacity is maximal in August, reaching 135 kWh monthly, which can ensure the load operating 4.0 h daily. While the generating capacity is minimal in December, reaching 73.70 kWh monthly, it can ensure the load operating 2.0 h daily. Expected generation capacity of designed PV system is presented in Table 4.

Table 4: Expected generation capacity of designed PV system.

Month	Horizontal Radiation kWh/m^2	Excepted Generation kWh
January	63.9	82.3
February	72.2	80.9
March	98.9	97.6
April	122.3	105.4
May	145.7	120.9
June	151.5	120.0
July	153.7	125.5
August	149.4	135.1
September	100.8	96.8
October	82.3	88.3
November	63.3	77.5
December	57.7	73.7
Year	1261.7	1203.8

5. Conclusion

Under the optimal experimental conditions, the ethanolamine concentration is 40%, and the absorption rate at the temperature of 40°C is 82.28%. The designed 2×40 t/h civil heating boiler flue gas absorption and desorption device has a diameter of 2.0 m and a tower height of 12.44 m. The filler is a Dg38 metal Pall ring. The system reduces CO_2 emissions by 42.8 t/year and regenerates CO_2 by 23.54 t/year. The system uses boiler flue gas to provide heats, accounting to 1.2×10^7 MJ/year for the absorption and desorption devices, and the energy provided by the solar energy system is 1.08×10^3 kWh/year.

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